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TECHNICAL NOTE

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FLAME STABILITY EFFECT OF GASES EJECTED INTO A STREAM FROM A BLUFF-BODY FLAMEHOLDER

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FLAME STABILITY EFFECT OF GASES EJECTED INTO A STREAM FROM A BLUFF-BODY FLAMEHOLDER

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SUMMARY

The effect of gas ejection from a bluff-body flameholder on the stability of premixed propane-air flames was studied using the following additives: hydrogen, air, and a premixed hydrogen-air mixture.

Hydrogen ejection from a flameholder promotes flame stability for fuel-lean mixtures but is very deleterious for fuel-rich mixtures. By ejecting a premixed hydrogen-air mixture, flame stability for fuel-rich mixtures was improved. Air ejection from a flameholder results in the shift of the equivalence ratio for maximum stability to richer mixtures and a small decrease in stability depending upon the amount of air ejected.

Varying the amount of hydrogen ejected from a flameholder did not affect the recirculation zone length for a gas velocity range of 150 to 300 feet per second.

On the basis of the air-ejection results a method of estimating the effective gas composition in the shear layer adjacent to the flameholder was presented. Comparison of the variation of the critical time and the reciprocal of the boundary velocity gradient for flashback with the effective gas composition indicates that the method is valid, and might be used to predict the effect of additives on the basis of fundamental combustion parameters.

INTRODUCTION

Recently, several investigators (refs. 1 and 2) have reported the effect on flame stability of adding small amounts of various gases to the flow near the flameholder. They showed that the blowoff velocity for a propane-air flame could be increased substantially by using additives like hydrogen or oxygen.

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Since very small amounts of additives are needed to produce large flame-stability improvement, this technique is a simple and economical method of promoting stability of flames in ramjet engines and afterburners. Thus it is desirable to investigate the optimum way to apply this technique. In addition, a better understanding of this technique would add to our knowledge of bluff-body flame stabilization, in general.

This research is conducted on the basis of the Zukoski and Marble flameholding model (ref. 3), which indicates that flame stability is controlled by the recirculation zone length, an aerodynamic factor and the critical time t_{cr}, a chemical factor. The term t_{cr} is that time which the fresh gas spends in the shear layer that separates the fresh gas stream from the recirculation zone at blowoff (see fig. 1), and is the ratio of the recirculation zone length to the blowoff velocity. Thus if the residence time t of the fresh gas in the shear layer is greater than t_{cr}, the flame is stable. If it is less, the flame blows out.

The effect of additives on the flame stability of a propane-air flame was studied in a 1- by 3-inch duct at reduced pressures, using a 1/2-inch-diameter flameholder. The additives used were hydrogen, air, and a premixed hydrogen-air mixture. Blowoff pressures (or blowoff velocities) were measured as a function of amount and type of additives. In addition, the effect of hydrogen additives on recirculation zone length and on t_{cr} was investigated.

On the basis of the effect of the air additive on flame stability, a stream area affected by the additive was estimated. This result was used to calculate the concentration of hydrogen additive in this stream area as a result of hydrogen ejection.

SYMBOLS

g_f flashback velocity gradient, sec

P blowoff pressure, atm

t time, sec

u blowoff velocity, ft/sec

φ equivalence ratio

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Subscripts:

cr critical

eff effective

min minimum

0 no additive

1 t_{cr} values at any pressure

2 t_{cr} values at pressure of 0.55 atm

APPARATUS AND PROCEDURE

The 1- by 3-inch duct with accessory equipment is shown in figure 2 (detailed description in ref. 4). Portions of the test-section sides were fitted with 1-inch-thick quartz windows to permit viewing of the flame. Critical-flow orifices were used to meter fuel and air and to maintain constant mass flow through the duct. Flames were blown off at constant mass flow by gradually reducing the pressure in the test section. The test-section pressure was regulated by adjustment of the exhaust-valve opening. The data were obtained as plots of blowoff pressures against fuel concentration at constant mass flow or Reynolds number. Blowoff velocities were calculated on the basis of stream flow past the flameholder.

The flameholder was an uncooled 1/2-inch-diameter brass cylinder extending across the short 1-inch dimension of the duct. The additive ejection openings consisted of twelve 1/16-inch-diameter holes arranged in two rows, parallel to the flameholder axis and set either 45° apart with ejection in an upstream direction (fig. 3(a)), 180° apart with ejection normal to main flow (fig. 3(b)), or 45° apart with ejection in a downstream direction (fig. 3(c)).

The additives used were hydrogen, air, and premixed hydrogen and air. The amount of additive was varied up to 3 "percent" where "percent" refers to percent of flow per unit projected flameholder area. Thus 1 "percent" of additive is equivalent to one-sixth of 1 percent of the total flow through the test section, since the flameholder projected area flow is one-sixth of the total flow. The additives were all metered by critical-flow orifices prior to entry into the flameholder.

All the additives were commercially available tanked gases, approximately 99 percent pure. Propane fuel (approx. 95 percent pure) and dried air were the main combustible mixture.

Recirculation zone lengths were measured by moving an electrically operated water-cooled probe in an upstream direction into the flame (fig. 2). When the ceramic-coated tip of the probe reached the recirculation zone, luminous yellow gases due to the vaporization of sodium salts in the ceramic were carried upstream from the probe tip into the recirculation zone. Further details of this technique are described in reference 4.

RESULTS

Blowoff Pressures

Effect of hydrogen additive. - The blowoff pressures for propane-air mixtures with increasing amounts of hydrogen were measured as a function of propane concentration at various mass flows corresponding to Reynolds numbers of 2.2 to 6.4×10^4. The hydrogen additive was ejected in the upstream position, as suggested in reference 1. These results are tabulated in table I. A typical flame-stability plot of blowoff pressure against fuel concentration φ is presented in figure 4 for Reynolds number of 4.3×10^4 (which represents a mean velocity of 159 ft/sec at pressure of 1 atm). The present data agree with those of references 1 and 2 in that the additive effect depends upon the fuel concentration of the main combustible mixture and upon the amount of hydrogen additive. In addition, at a large hydrogen-additive flow, in lean propane-air mixtures, and at high mass flows, there exist residual flames as described in reference 2. These are small flames and are very stable, but do not propagate into the main portion of the combustible mixture. Thus, in figure 4 the dotted lines at very lean φ and moderately low pressure represent data for the residual flame blowoff and the dashed lines represent data for conditions at which the stabilized propane-air flame first showed a marked decrease in its wake size. Thus, the true pressure of blowoff P_{bo} plotted against φ curve for very lean mixtures and high Reynolds number is difficult to establish precisely, but it probably lies very close to the dashed line mentioned previously.

From the blowoff pressure data, blowoff velocities for various φ were calculated at constant pressure. From these results, blowoff velocity ratios u/u_0 (where u is the blowoff velocity for a given propane concentration and flow of additive and u_0 is the blowoff velocity for the same propane concentration with no additive) are obtained and plotted against concentration of hydrogen additive in terms of percent concentration in figure 5. For the three fuel concentrations compared at constant pressure, the lean mixture of 0.9 φ showed the maximum flame stability gain of over four in terms of the blowoff velocity ratio. This gain decreases as φ is increased to 1.1. For φ of 0.9 and 1.0 the optimum concentration of additive is about 2 percent.

Note that the stability gain is usually less for the higher pressure, or the higher Reynolds number.

The fact that the hydrogen-additive effect is very dependent upon equivalence ratio (being especially favorable for a leaner-than-stoichiometric mixture) has also been mentioned previously in references 1 and 2. This can be explained as follows: Since the Zukoski and Marble flameholding concept (ref. 3) indicates that flame stability depends essentially upon certain conditions prevailing in the shear layer (fig. 1), the blowoff velocity thus depends on the composition only of the gases flowing into the shear layer, and not on the composition of the main combustible stream mixture. Thus, for lean mixtures, when a small amount of hydrogen is added to the region near the flameholder the composition of the mixture flowing into the shear layer is changed closer to an optimum mixture and thus blowoff velocity is increased.

Effect of hydrogen-air additive. - The hydrogen-additive results indicated that the effect of the additive is very dependent upon the stoichiometry of the gases entering the shear layer, and that addition of hydrogen to fuel-rich mixtures will decrease stability. This effect should not occur if air is added to the hydrogen ejected from the flameholder. A premixed hydrogen-air mixture (49 percent hydrogen by volume) was used as the additive. The results for two Reynolds numbers are listed in table II. Figure 6 is a typical plot of blowoff pressure against equivalence ratio for the two types of additives. The minimum in the blowoff pressure curve for the hydrogen-air additive is observed to shift to richer mixtures, as expected.

Effect of air additive. - When hydrogen is ejected from the flameholder, both stoichiometry and the chemical properties of the mixture entering the shear layer are changed. In order to simplify this situation, air can be ejected as an additive, since then only stoichiometry is changed. Figure 7 shows the result of air addition to the propane-air flames. Two effects are observed. One is the expected shift of the minimum blowoff pressure (corresponding to maximum blowoff velocity) to richer mixtures as the amount of air added is increased. The other effect is the increase in the minimum blowoff pressure (corresponding to decrease in maximum blowoff velocity) as air addition increases. This second effect must be the result of cooling of the shear layer.

Effect of positions of additive ejection. - Since the additive effect on flame stability depends upon the additive entering the shear layer for its influence, the position of additive ejection into the stream may be important. In order to test this, flame-stability data for two other ejection positions (side (fig. 3(b) and downstream (fig. 3(c)) were obtained and are listed in table III. The effects of the

three positions for 1- and 2-percent concentrations of hydrogen additives are compared in figures 8(a) and (b). The effect of position is small and depends upon equivalence ratio of the main mixture. For very lean mixture the order of effectiveness is as follows: downstream, side, and upstream. For rich mixtures the order of effectiveness is in reverse order: upstream, side, and downstream. Thus, for maximum improvement of lean mixture blowoff, ejection should be directly into the recirculation zone. For rich mixtures better results are obtained by ejection into the unburned gas region since this position probably permits the least amount of hydrogen additive to enter the already fuel-rich shear layer.

Recirculation Zone Length

Small flows of additive would not be expected to affect the recirculation zone length. However, it was thought best to eliminate the possibility. Consequently, the effect of hydrogen additive on the recirculation zone of some propane-air flames at various gas velocities were investigated using the recirculation zone length measuring technique described in reference 4. The results of these measurements are shown in figure 9. It was observed that the length for a 1/2-inch-diameter flameholder and the range of gas velocities of 150 to 300 feet per second were nearly independent of gas velocity and varying amounts of hydrogen additive. A dashed line representing a length of 1.7 inches, previously established for a 1/2-inch-diameter flameholder in the same duct for a propane-air flame (ref. 4), is drawn through the data.

DISCUSSION

According to the Zukoski and Marble flameholding concept (ref. 3), continuous ignition of the fresh gas from the gas stream by the hot combustion products occurs in the shear layer separating the recirculation zone and the free stream (fig. 1). Whether or not a flame is stabilized depends upon the time t (the ratio of recirculation zone length to the free stream velocity) that the fresh gas resides in the shear layer, or mixing zone. If t is too small, insufficient fresh gas is ignited in the shear layer to maintain flame propagation, and blowoff occurs. Thus t must be equal to or greater than t_{cr}, which is the critical time required to maintain flame propagation and is the ratio of the recirculation zone length to the blowoff velocity. The important factors affecting flame stability are the recirculation zone length, an aerodynamic parameter, and a chemical parameter t_{cr}.

Since it was previously established that the recirculation zone length is substantially independent of gas ejection from the flameholder

the effects of additive on flame stability are principally chemical ones. Thus flame stability is determined essentially by the additive affecting the gas composition in some thin layer adjacent to the flameholder. The resulting gas composition in this thin layer may be estimated from the following information: (1) effective area of thin layer, (2) flow rate of main combustible mixture through a given duct, and (3) flow rate of additive from the flameholder. The only unknown factor ((1) effective area of the thin layer) may be estimated by the following method.

Air may be added to the propane-air stream either by a spray bar located far enough upstream to ensure thorough mixing with the main stream before it reaches the flameholder, or by ejection from the flameholder using the additive technique. The equivalence ratio of the original propane-air stream at which the minimum blowoff pressure (maximum blowoff velocity) occurred will shift to richer mixtures as the amount of air added by either means is increased. For a given equivalence-ratio shift the amount of added air (cu ft/hr) from the flameholder may be compared with the amount of "dilution" air (cu ft/hr), which would have to be added from a spray bar at some upstream distance from the flameholder. Such a comparison, based on figure 7, is shown in the following table:

Amount of air ejected from flameholder, "percent"	Amount of air ejected from flameholder, cu ft/hr	Equivalence ratio of minimum blowoff pressure, φ_{min}	Calculated dilution air to cause φ_{min} shift, cu ft/hr	Ratio of calculated air flow to actual added air flow
0	0	1.025	0	--
.52	9	1.06	339	38
1.05	18	1.14	1065	59
2.00	34	1.14	1065	30
2.95	50	1.30	2590	52
				average = 45

Thus, adding air by ejection from the flameholder is about 45 times more effective than the method of mixing air with the main propane-air stream by means of a spray bar located upstream of the flameholder. (This factor of 45 observed holds only for the 1- by 3-inch duct since the calculated dilution air to cause φ_{min} shift in the preceding table is based on the cross-sectional area of this duct.) Consequently, the effective area into which the additive gas from the flameholder flows is 1/45 of the tunnel area at the flameholder, or 0.056 square inch. The effective thickness of the layer on each side of the 1/2-inch flameholder is about 0.028 inch.

The preceding method may be applied to some of the data of reference 2, in which propane additive was added to a propane-air flame in a 1/2- by 2-inch duct using a 0.2-inch-diameter flameholder. For the data of reference 2 the additive effective factor was 162, giving an effective area of about 0.006 square inch and a layer thickness of 0.006 inch. Thus, the layer thickness decreases by a factor of five when the flameholder diameter is reduced from 0.5 to 0.2 inch.

It is conceivable that the effective layer thickness is related to the boundary-layer thickness. A calculation of boundary-layer thickness on the basis of reference 5 for the two different-size flameholders shows that the boundary-layer thickness for the 1/2-inch flameholder is about ten times larger than that for the 0.2-inch flameholder. This may indicate some relation between the two kinds of layer.

The importance of a knowledge of the effective layer thickness is that it can be used to calculate the gas composition which governs the stability of the flame. Thus, the flow of additive which yields an effective gas composition corresponding to the highest possible blowoff velocity can be calculated, provided that the effect of gas composition on blowoff velocity is known.

An indirect verification of this method of estimating the effective gas composition φ_{eff} in the shear layer can be made, based on the fact that at constant pressure, the critical time t_{cr} and $1/g_f$ the reciprocal of the critical flashback velocity gradient vary with φ in approximately the same manner. Reference 6 has also noted the proportionality of these two quantities. This might be expected, since they are dimensionally identical.

The procedure used was first to calculate the effective gas composition φ_{eff} at blowoff for various flows of additive. For convenience, blowoff data at a constant pressure of 0.55 atmosphere were used. Then, from the blowoff velocities and the recirculation zone length (1.7 in.), values for the critical time t_{cr} corresponding to each effective gas composition were calculated. These results are listed in table IV. Finally, values of $1/g_f$ for each effective gas composition were calculated from the data of references 7 and 8, using an average pressure exponent of 1.05 to find g_f at 0.55 atmosphere. Now, if the effective gas composition is correct, a correlation should be observed between t_{cr} and $1/g_f$. The plot of t_{cr} against $1/g_f$ shown in figure 10 shows this to be true. The critical time is equal to about one-third of $1/g_f$. In principle, this procedure could be reversed to find approximate blowoff velocities for various flows of additive from a knowledge of the boundary velocity gradient for flashback, the recirculation zone length, and the effective layer thickness. It should be mentioned that the correlation plot of figure 10 fails completely when a number twice 45 is used as the effective factor, indicating that the effective factor of 45 for this apparatus has been established to within about ±50 percent.

The foregoing analysis and experimental work showed that small amounts of additive can give a large gain in stability limits. In addition this study demonstrated a method of predicting the effect of additive on flame stability from the basis of a fundamental combustion property.

SUMMARY OF RESULTS

An investigation of the effect of gas ejection from a flameholder on bluff-body flame stabilization was completed with the following results:

1. Hydrogen ejected from a flameholder is very effective in stabilizing fuel-lean propane-air flames. For example, the blowoff velocity at 0.5 atmosphere for a propane-air mixture with an equivalence ratio of 0.9 was increased by about a factor of over four for a hydrogen flow of 33 cubic feet per hour, which is about 0.4 percent (by weight) of the propane fuel flow.

2. Hydrogen ejection reduces the stability of fuel-rich flames. The use of a premixed hydrogen-air additive improves flame stability of even fuel-rich mixtures.

3. The effects of air ejection from a flameholder are: (a) the equivalence ratio for maximum blowoff velocity is shifted to richer mixture and (b) the maximum blowoff velocity is decreased depending upon amount of air ejected.

4. Varying amounts of hydrogen additive ejected from a flameholder into a propane-air flame had no effect on the recirculation zone length. Thus, according to the Zukoski and Marble flameholding model the additive influenced only the critical time, a chemical factor.

5. On the basis of the air-ejection results a method of estimating the effective gas composition in the shear layer adjacent to the flameholder was developed. The method was used to estimate the effective composition for hydrogen addition. The critical times for these effective compositions were found to be proportional to another time, which characterizes combustion reactivity, the reciprocal of the critical flashback boundary velocity gradient. This result serves to confirm the method of estimating shear-layer composition. Furthermore, it suggests that the performance of flameholders with additive injection may be estimated on the basis of a more easily attainable fundamental combustion property.

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National Aeronautics and Space Administration
Cleveland, Ohio, March 11, 1959

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TABLE I. - BLOWOFF PRESSURE FOR PROPANE-AIR FLAMES WITH VARIOUS HYDROGEN-ADDITIVE CONCENTRATIONS

[Upstream position.]

Reynolds number $\times 10^4$	Mean gas velocity at a pressure of 1 atm, ft/sec	Equivalence ratio, φ	Blowoff pressure, atm	Hydrogen additive, percent
2.2	81	0.76	0.727	0
			.744	
		.85	.608	
		1.00	.528	
			.532	
			.539	
		1.10	.553	
			.557	
		1.23	.622	
			.642	
		1.34	.710	
			.772	
			.768	
		.60	.923	1.0
		.65	.632	
		.74	.488	
			.495	
		.85	.437	
			.444	
		.97	.461	
		1.08	.485	
			.488	
		1.21	.633	
			.591	
		1.33	.710	
		.58	.539	1.5
			.546	
		.72	.437	
			.444	
		.73	.458	
		.83	.396	
		.84	.403	
		.98	.417	
			.406	
		1.09	.450	
			.488	
			.471	
		1.21	.608	
			.614	
		.59	.403	2.0
			.393	
		.74	.334	
		.86		
		.98	.369	
			.375	
		1.08	.484	
			.495	
		1.19	.625	
		1.20	.642	
		.58	.369	2.7
			.383	
		.61	[a].314	
			[a].300	
		.74	.283	

Reynolds number $\times 10^4$	Mean gas velocity at a pressure of 1 atm, ft/sec	Equivalence ratio, φ	Blowoff pressure, atm	Hydrogen additive, percent
2.2	81	0.74	0.290	2.7
		.85	.314	
		1.09	.451	
		1.22	.622	
			.666	
4.5	159	.74	~1.000	0
		.84	.796	
			.811	
			.801	
		.85	.726	
			.750	
		.95	.635	
			.649	
		.96	.652	
		1.09	.659	
		1.11	.661	
			.676	
			.659	
		1.13	.644	
		1.22	.722	
			.729	
			.726	
		1.23	.743	
		1.24	.796	
			.756	
		.72	.874	.6
		.74	.756	
			.729	
			.712	
		.83	.621	
		.84	.625	
			.549	
			.586	
			.593	
		.95	.539	
		.96	.553	
		1.07	.621	
		1.08		
		1.11	.627	
			.596	
		1.19	.744	
		1.20	.771	
		.61	~1.000	1.0
		.71	.590	
			.597	
		.74	.596	
			.569	
		.83	.519	
			.529	
		.96		
			.519	
		1.11	.593	
			.583	
		1.20	.778	
		.60	[a].372	2.1
			.497	

[a]Residual flame blowoff.

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TABLE I. - Concluded. BLOWOFF PRESSURE FOR PROPANE-AIR FLAMES WITH VARIOUS HYDROGEN-ADDITIVE CONCENTRATIONS

[Upstream position.]

Reynolds number $\times 10^4$	Mean gas velocity at a pressure of 1 atm, ft/sec	Equivalence ratio, φ	Blowoff pressure, atm	Hydrogen additive, percent
4.3	159	0.60	0.493	2.1
		.72	.388	
			.369	
			.375	
		.73	.378	
		.84	.385	
			.399	
			.392	
		.95	.446	
		.96	.437	
			.440	
		.97	.446	
		1.08	.631	
			.608	
		1.09	.595	
			.635	
			.601	
		1.20	.792	
			.802	
		.52	[a].314	3.1
			[a].317	
		.60	(a)	
		.61	[a].321	
			.365	
			.392	
		.73	.365	
			[a].348	
			[a].334	
		.74	.388	
			.355	
		.84	.382	
			.375	
		.85	.365	
			.372	
		.96	.456	
			.488	
			.485	
		1.09	.693	
			.676	
		1.12	.692	
			.726	
			.669	
			.651	
		1.20	.802	
			.792	
6.4	236	.83	.829	0
		.84	.847	
			.852	
			.761	
			.768	
		.94	.733	
			.710	
		.95	.723	
		1.07	.734	
			.727	
		1.08	.792	
			.788	
		1.16	.829	
		1.17		
		.47	[a].666	1.6

Reynolds number $\times 10^4$	Mean gas velocity at a pressure of 1 atm, ft/sec	Equivalence ratio, φ	Blowoff pressure, atm	Hydrogen additive, percent
6.4	236	0.47	[a]0.676	1.6
		.54	[a].556	
			[a].553	
		.55	.922	
			.888	
		.60	[a].519	
			[a].522	
		.63	.632	
		.70	.505	
		.71	.495	
		.72	.488	
		.84	.485	
			.495	
		.94	.512	
			.518	
		1.08	.768	
			.762	
		.36	[a].655	2.0
			[a].642	
		.41	[a].539	
			[a].532	
		.48	[a].495	
			[a].488	
		.54	[a].461	
			(a)	
		.55	.683	
			.698	
		.61	.451	
		.63	.573	
			.597	
		.64	.457	
		.71	.474	
			.495	
		.72	[a].451	
			[a].437	
		.83	.471	
			.478	
			.471	
		.95	.505	
			.512	
		1.07	.757	
		.34	[a].386	3.0
		.48	[a].382	
			[a].386	
		.53	.682	
			.699	
		.56	[a].382	
			[a].386	
		.58	.597	
		.59	.590	
		.61	[a].410	
			[a].403	
		.70	.403	
			.416	
		.71	.420	
			.416	
		.84	.464	
		.94	.573	
			.587	
		.792	1.080	

[a]Residual flame blowoff.

TABLE II. - BLOWOFF PRESSURES FOR PROPANE-AIR FLAMES USING HYDROGEN-AIR ADDITIVE AND HYDROGEN ADDITIVE ALONE

[Downstream position.]

Reynolds number $\times 10^4$	Mean gas velocity at a pressure of 1 atm, ft/sec	Equivalence ratio, φ	Blowoff pressure, atm	Additive, percent
Hydrogen-air additive				
4.4	162	0.80	0.884	0
		.86	.711	
			.738	
		.97	.670	
			.694	
		1.09	.687	
			.697	
		1.22	.762	
			.772	
		.65	.627	1.1
		.79	.468	
		.90	.424	
		1.06	.434	
		1.20	.492	
		1.30	.864	
		.61	.763	2.0
		.68	.492	
		.97	.390	
		1.01	.366	
		1.13	.390	
		1.24	.765	
		1.33	>.950	
		.63	.492	3
		.72	.449	
		.88	.381	
		1.01	.347	
		1.13	.370	
		1.25	.425	
		1.31	.966	
6.5	238	.61	.780	1.9
		.73	.661	
		.87	.551	
		.88	.502	
		1.00	.475	
		1.12	.483	
		1.14	.414	
		1.18	.864	
Hydrogen additive				
4.3	159	0.61	0.502	1.0
		.69	.424	
		.85	.434	
		1.00		
		1.12	.617	
		1.20	.831	
		.55	.525	1.5
		.67	.366	
		.79	.356	
		.95	.424	
		1.07	.556	
		1.17	.763	
6.4	237	.63	.620	.9
		.74	.542	
		.77	.533	
		.88	.550	
		1.01	.592	
		1.12	.830	

TABLE III. - BLOWOFF PRESSURES FOR PROPANE-AIR FLAMES FOR VARIOUS HYDROGEN-ADDITIVE CONCENTRATIONS

[Side and downstream positions; Reynolds number, 4.3×10^4; mean gas velocity, 159 ft/sec at pressure of 1 atm.]

Position	Equivalence ratio, φ	Blowoff pressure, atm	Hydrogen additive, percent
Side	0.62	0.912	0.5
	.65	.861	
	.72	.568	
	.73	.591	
	.84	.480	
	↓	.500	
	.96	↓	
	↓	.524	
	1.08	.591	
	↓	.581	
	1.09	.584	
	1.19	.705	
	1.20	.669	
	1.22	.686	
	1.31	.878	
	.50	[a].348	1.0
	.62	[a].355	
	↓	[a].355	
	.74	[a].348	
	↓	[a].361	
	.84	.392	
	↓	.378	
	.97	.456	
	↓	.453	
	1.11	.591	
	↓	.618	
	1.21	.736	
	↓	.726	
	.61	[a].270	2.1
	↓	[a].277	
	.72	[a].304	
	↓	[a].314	
	.85	.345	
	↓	.348	
	.97	.490	
	↓	.483	
	1.06	.635	
	↓	.615	
	1.18	.794	
	↓	.804	
	.51	[a].263	
	↓	[a].203	
	.60	[a].270	
	↓	[a].277	
	.71	[a].297	
	↓	[a].297	
	.85	.392	
	↓	.388	
	.96	.547	
	↓	↓	
	1.11	.750	
Downstream	.53	[a].364	.5
	.61	[a].364	
	.73	[a].371	
	.84	[a].527	
	.97	[a].524	
	1.10	.571	
	↓	.585	
	1.20	.782	
	↓	.765	
	.53	[a].265	1.0
	.61	[a].296	
	.74	[a].326	
	.85	.418	
	.98	.459	
	1.09	.697	
	.53	[a].262	2.1
	.62	[a].279	
	.73	[a].303	
	.85	.364	
	.99	.537	
	↓	.527	
	1.09	.758	
	.53	[a].262	3.1
	.62	[a].282	
	.74	[a].323	
	.86	.449	
	↓	↓	
	.97	.653	
	↓	↓	
	1.08	.857	

[a]Residual flame blowoff.

TABLE IV. - COMPARISON OF CALCULATED CRITICAL t_{cr} VALUES AGAINST RECIPROCAL OF FLASHBACK VELOCITY GRADIENT FOR VARIOUS PROPANE-HYDROGEN-AIR MIXTURES

Main mixture equivalence ratio, φ	Hydrogen additive, percent concentration	Effective concentration			Effective equivalence ratio, φ_{eff}	Critical time at any pressure, $t_{cr,1}$, sec	Pressure for $t_{cr,1}$ values, atm	Critical time at a pressure of 0.55 atm, sec	Flashback velocity gradient at a pressure of 1 atm, g_f, sec^{-1} (a)	$1/g_f$ at a pressure of 1 atm, sec	$1/g_f$ at a pressure of 0.55, atm, sec
		Propane C_3H_8, percent	Hydrogen additive, percent	Air, percent							
0.7	0	2.86	0	97.14	0.70	--------	----	--------	[b]130	7.00×10^3	13.1
	.6	2.73	4.39	92.88	.81	--------	----	--------	800	1.25	2.34
	1.0	2.66	7.11	90.23	.89	0.89×10^3	0.55	0.89×10^3	[c]1500	.67	1.25
	2.0	2.48	13.27	85.25	1.06	.44	.40	.21	[c]3200	.31	.58
	3.0	2.33	18.67	79.00	1.26	.30		.18	4000	.25	.47
.8	0	3.25	0	96.75	.80	1.07	.70	1.80	[a]240	4.20	7.85
	.6	3.11	4.39	92.50	.91	.56	.63		1000	1.00	1.87
	1.0	3.02	7.11	89.87	.99	.57	.50	.42	[c]1500	.67	1.25
	2.0	2.82	13.27	83.91	1.18	.46	.35	.10	1800	.56	1.05
	3.0	2.64	18.67	78.69	1.36	.35		.17	4000	.25	.47
.9	0	3.65	0	96.35	.90	.87	.60	1.75	[a]350	2.90	5.42
	.6	3.49	4.39	92.12	1.01	.49	.55	.49	[c]1300	.77	1.44
	1.0	3.39	7.11	89.50	1.09	.68	.45	.38	[c]1600	.63	1.17
	2.0	3.17	13.27	83.56	1.28	.35		.22	1750	.57	1.07
	3.0	2.97	18.67	78.36	1.47	.34		.27	[c]1000	1.00	1.87
1.0	0	4.04	0	95.96	1.00	.64	.60	.97	500	2.00	3.74
	.6	3.86	4.39	91.75	1.12	.49	.55	.49	[c]1350	.74	1.38
	1.0	3.75	7.11	89.14	1.19	.55	.50	.37	[c]1350		1.38
	2.0	3.50	13.27	83.23	1.38	.47		.36	1200	.83	1.55
	3.0	3.29	18.67	78.04	1.57	.43		.43	[c]900	1.11	2.08
1.1	0	4.42	0	95.58	1.10	.91	.55	.91	700	1.43	2.67
	.6	4.23	4.39	91.38	1.20	.56	.62		800	1.25	2.34
	1.0	4.11	7.11	88.78	1.29	.68	.55	.68	800		2.34
	2.0	3.83	13.27	82.90	1.48	.71		.71	1300	.77	1.44
	3.0	3.59	18.67	77.74	1.67	.67		.67	[c]900	1.11	2.07
1.2	0	4.80	0	95.20	1.20	.86	.65	1.50	[c]640	1.56	2.92
	.6	4.58	4.39	90.03	1.33	.68	.76		[c]900	1.11	2.08
	1.0	4.46	7.11	88.43	1.39	.88	.65	1.10	640	1.56	2.92
	2.0	4.16	13.27	82.57	1.58	.92		1.07	700	1.43	2.67
	3.0	3.90	18.67	77.43	1.77	1.07		1.40	[c]550	1.85	3.46

[a]Flashback velocity gradient g_f data based mainly on ref. 9.
[b]Lewis von Elbe data, ref. 7.
[c]Interpolated data.

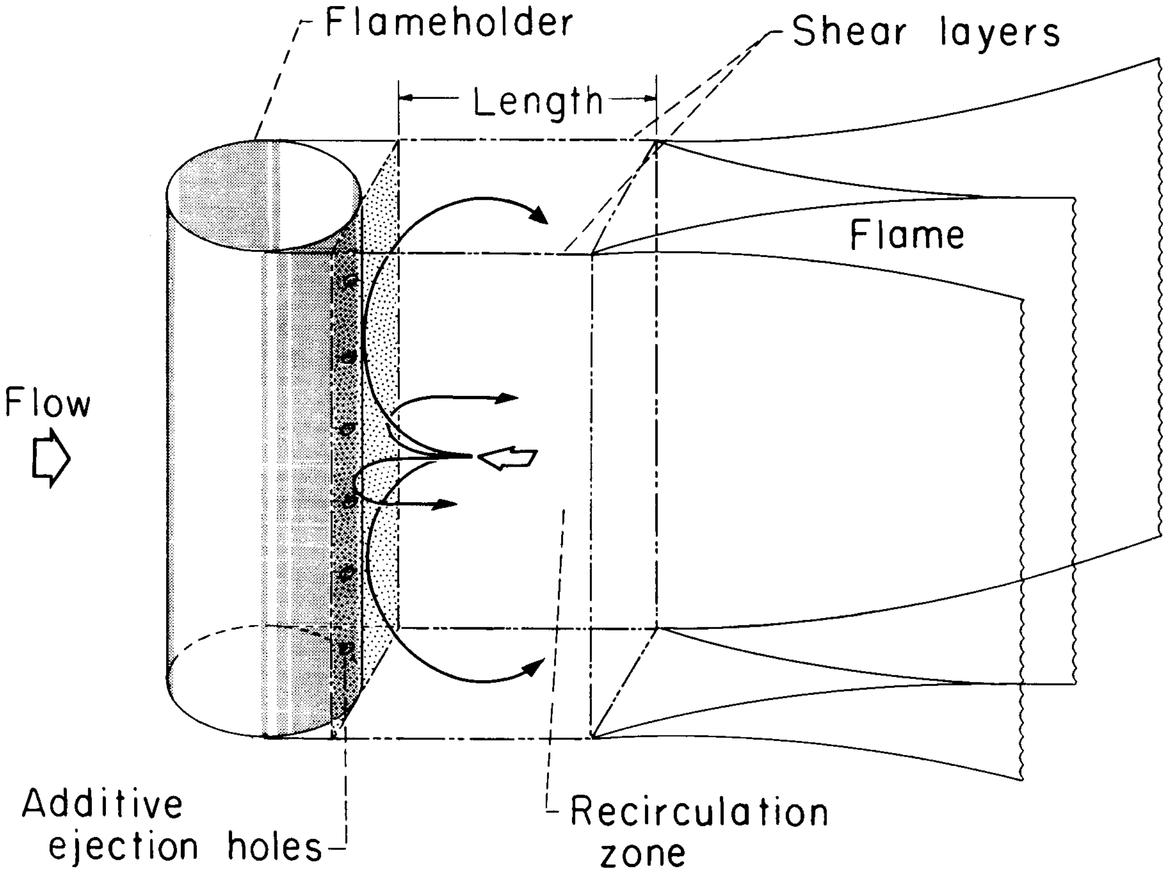

Figure 1. - Zukoski and Marble flameholding model.

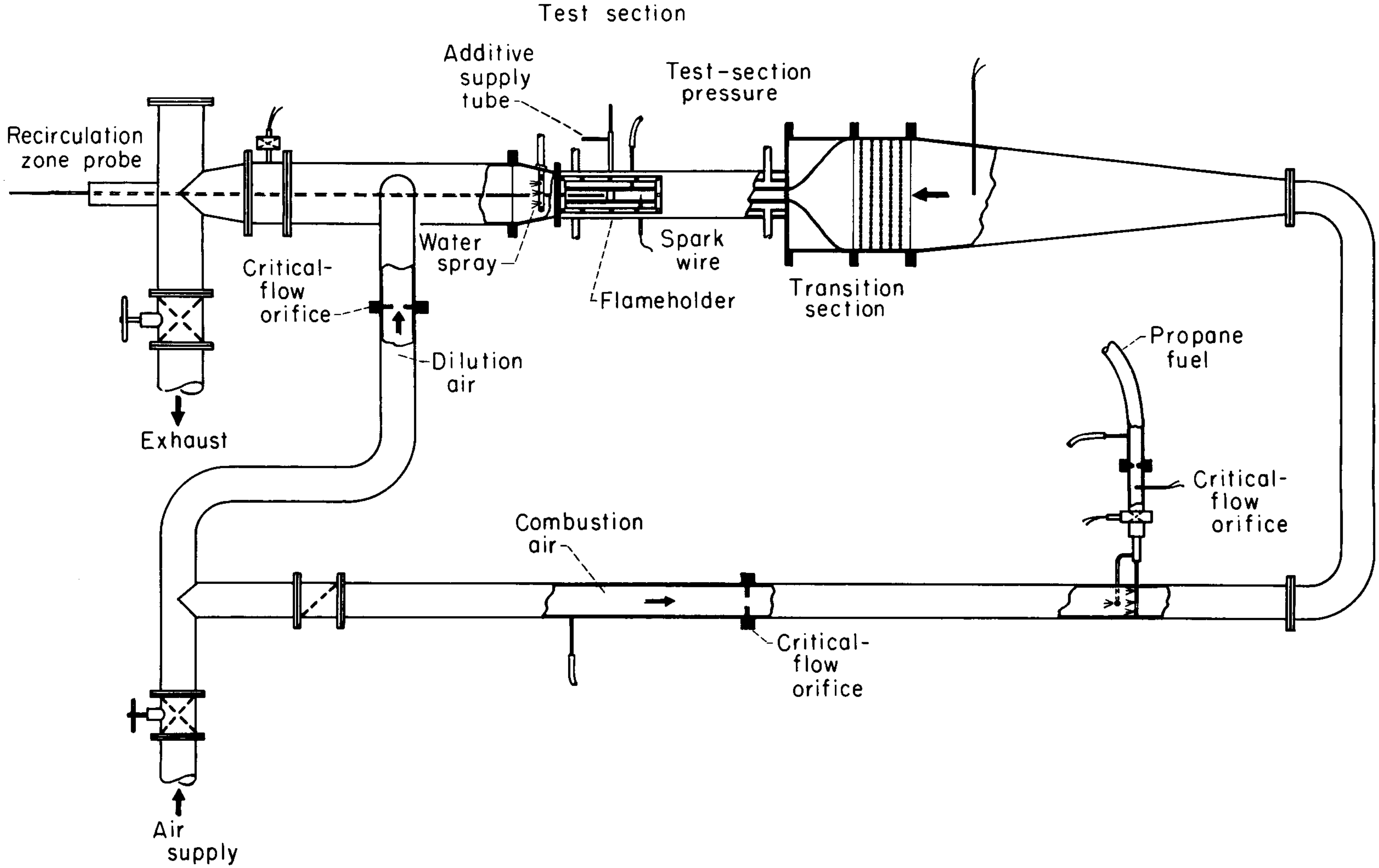

Figure 2. - Low-pressure flame stability apparatus.

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CM-3 back

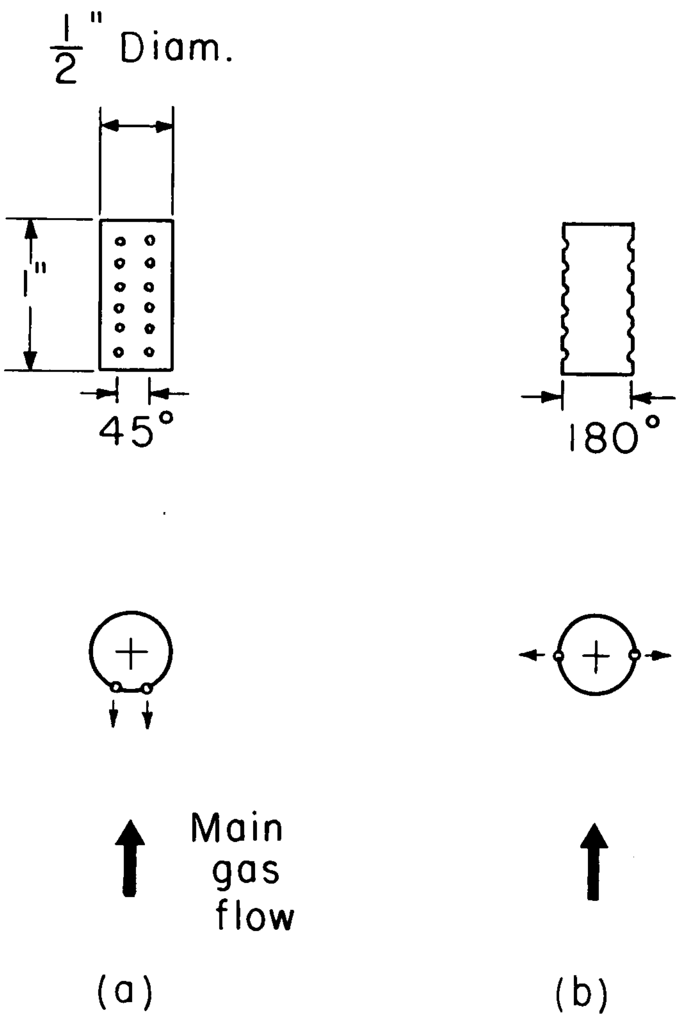

Figure 3. - Flameholders.

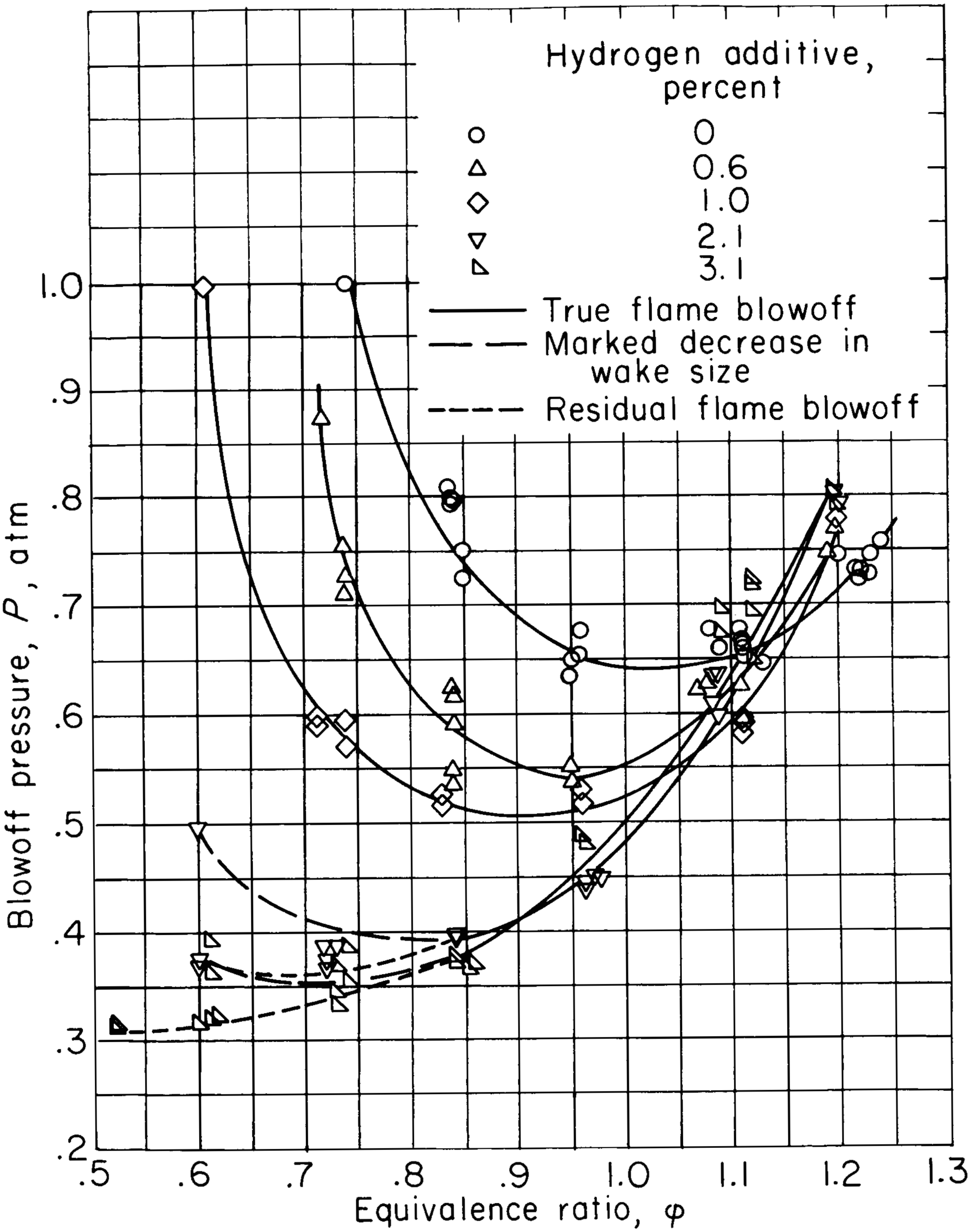

Figure 4. - Effect of hydrogen additive on propane-air flame stability. Upstream injection; Reynolds number, 4.3×10^{4}; mean velocity, 159 feet per second at a pressure of 1 atmosphere.

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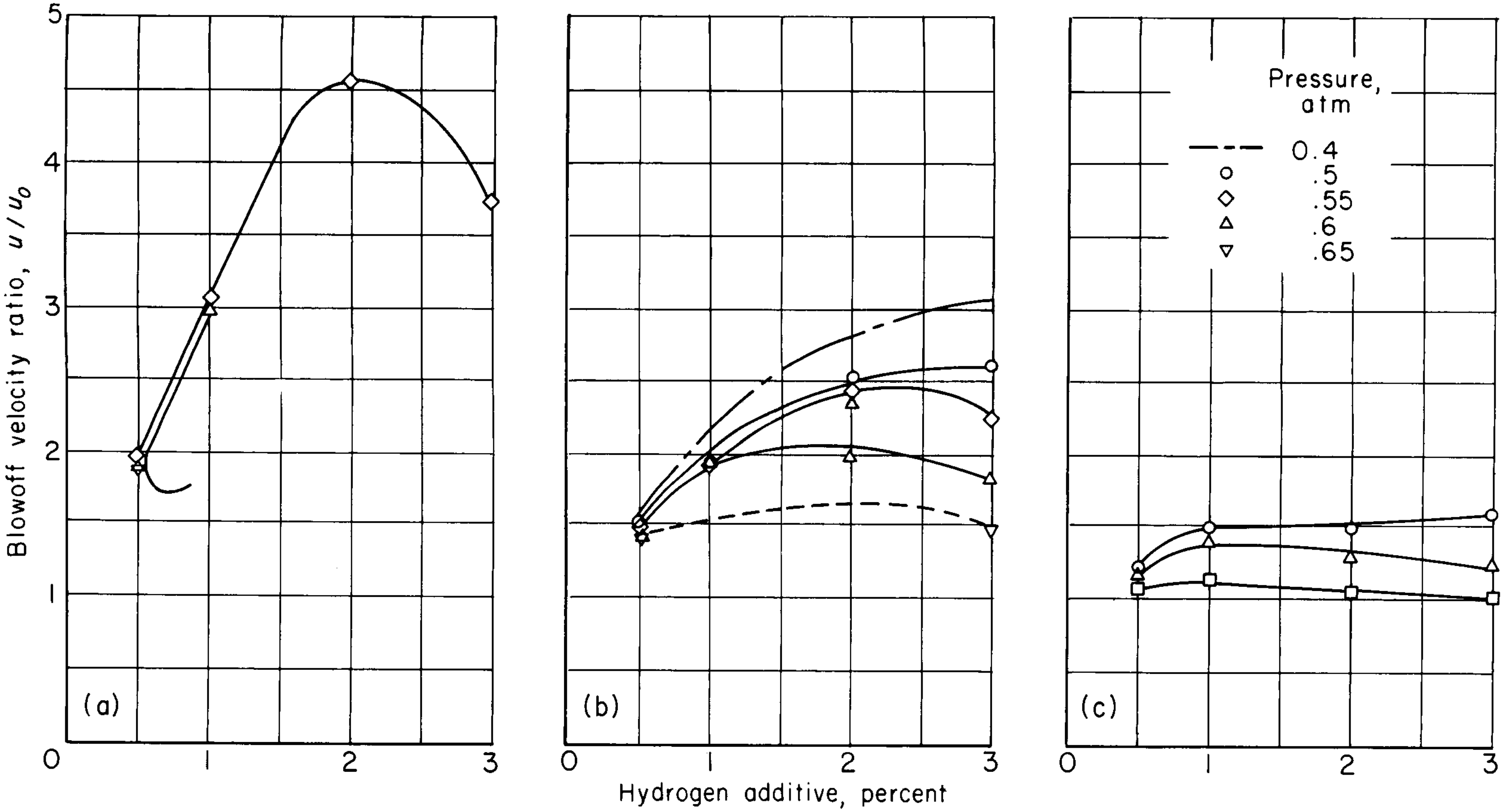

(a) Equivalence ratio, φ, 0.9.

(b) Equivalence ratio, φ, 1.0.

(c) Equivalence ratio, φ, 1.1.

Figure 5. - Effect of hydrogen additive on blowoff velocity for various equivalence ratios.

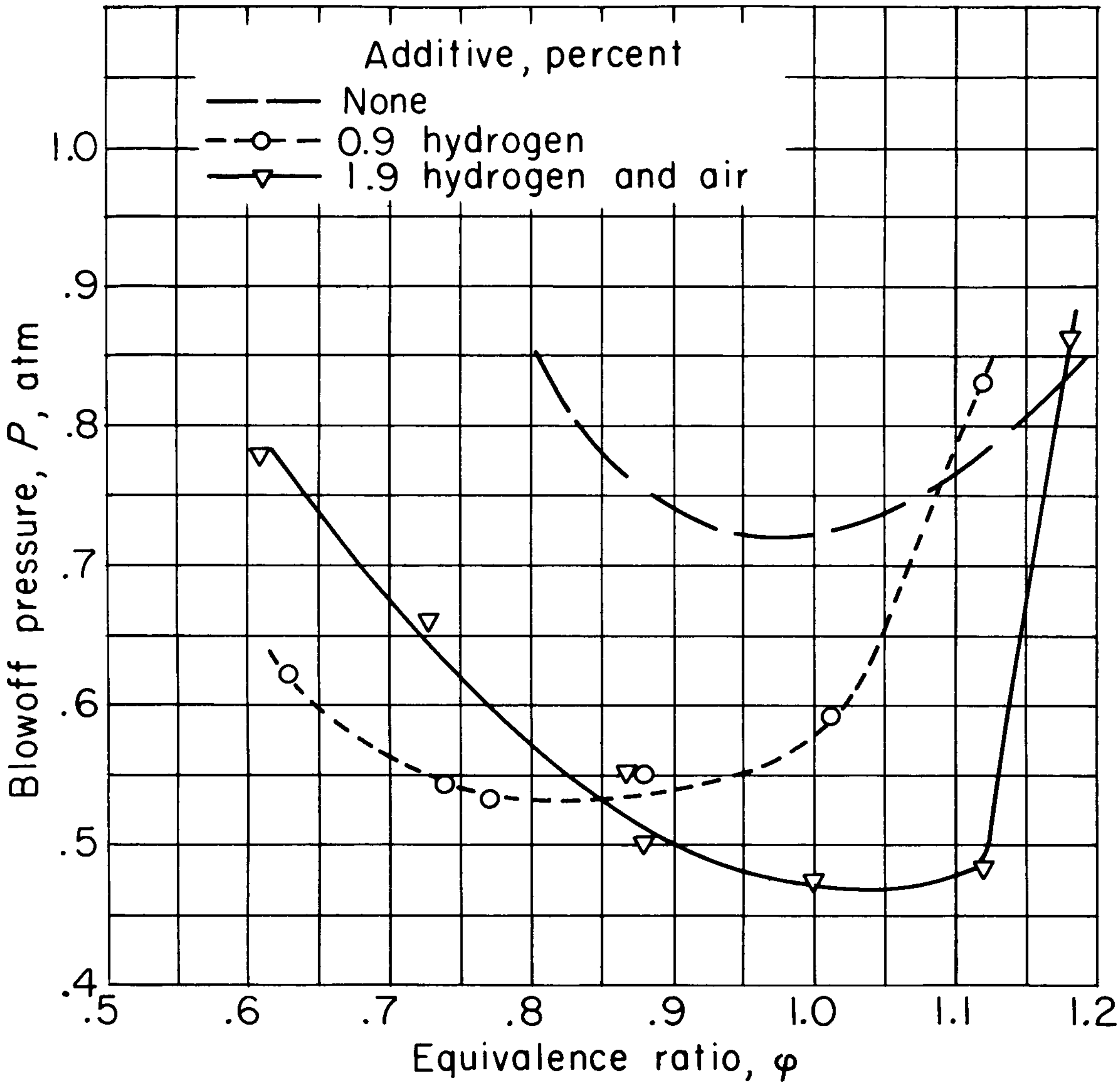

Figure 6. - Comparison of effects of hydrogen-air and hydrogen additive on propane-air flame stability. Reynolds number, 6.5×10^4; mean velocity of 238 feet per second at a pressure of 1 atmosphere.

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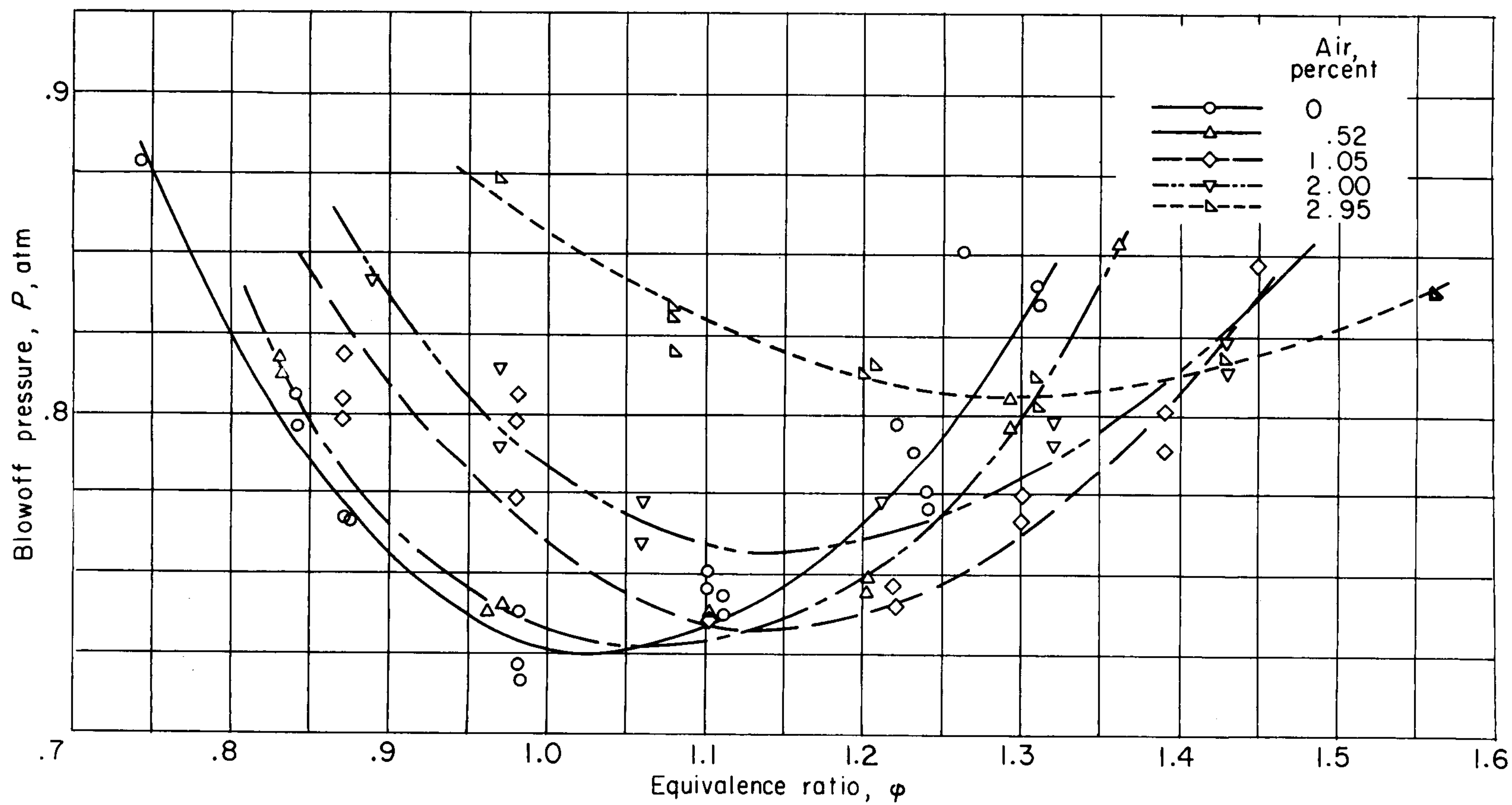
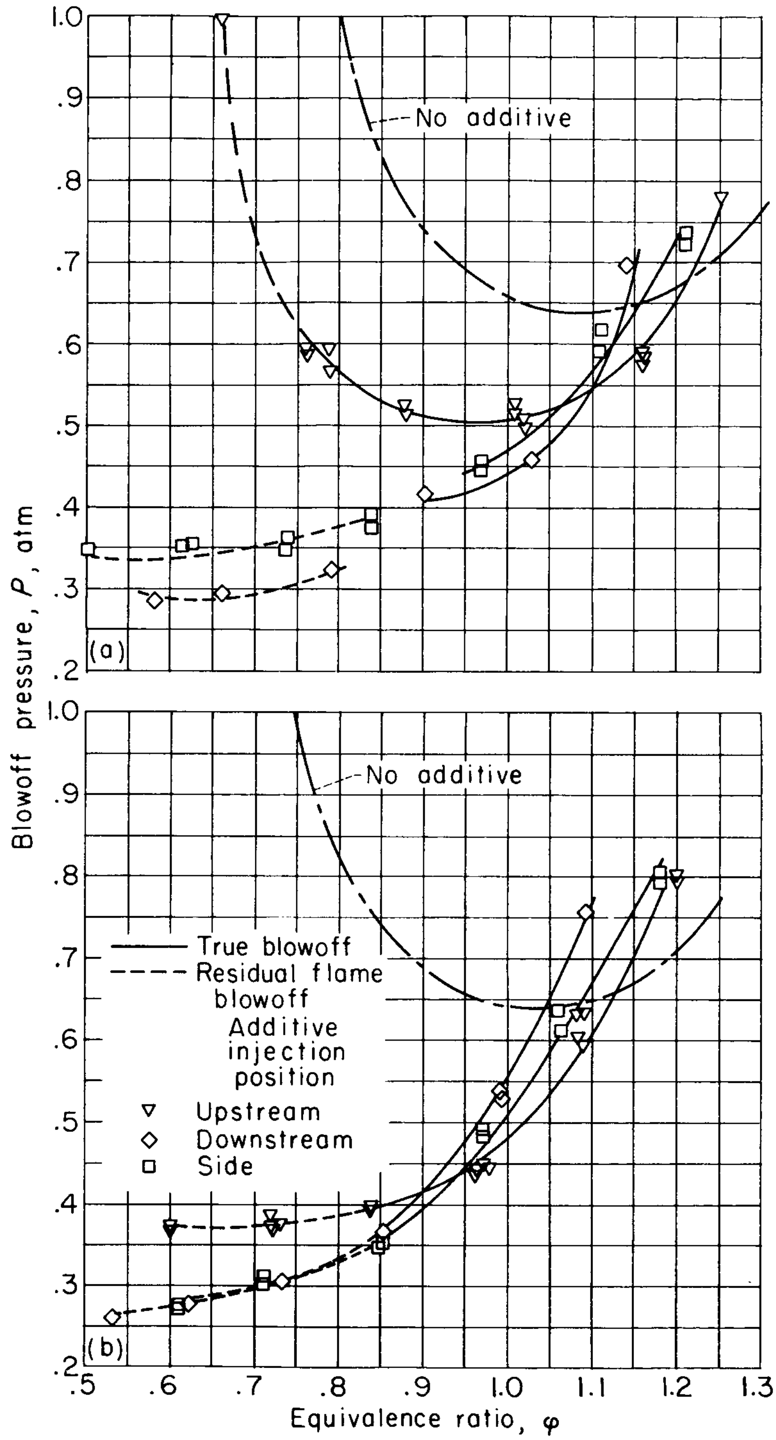


Figure 7. - Effect of air additive on flame stability of propane-air flame. Downstream injection; Reynolds number, 4.37×10^4.



(a) Hydrogen additive concentration, 1 percent.

(b) Hydrogen additive concentration, 2 percent.

Figure 8. - Effect of additive injection positions on propane-air flame stability. Reynolds number, 4.3×10^{4}; mean velocity, 159 feet per second at a pressure of 1 atmosphere.

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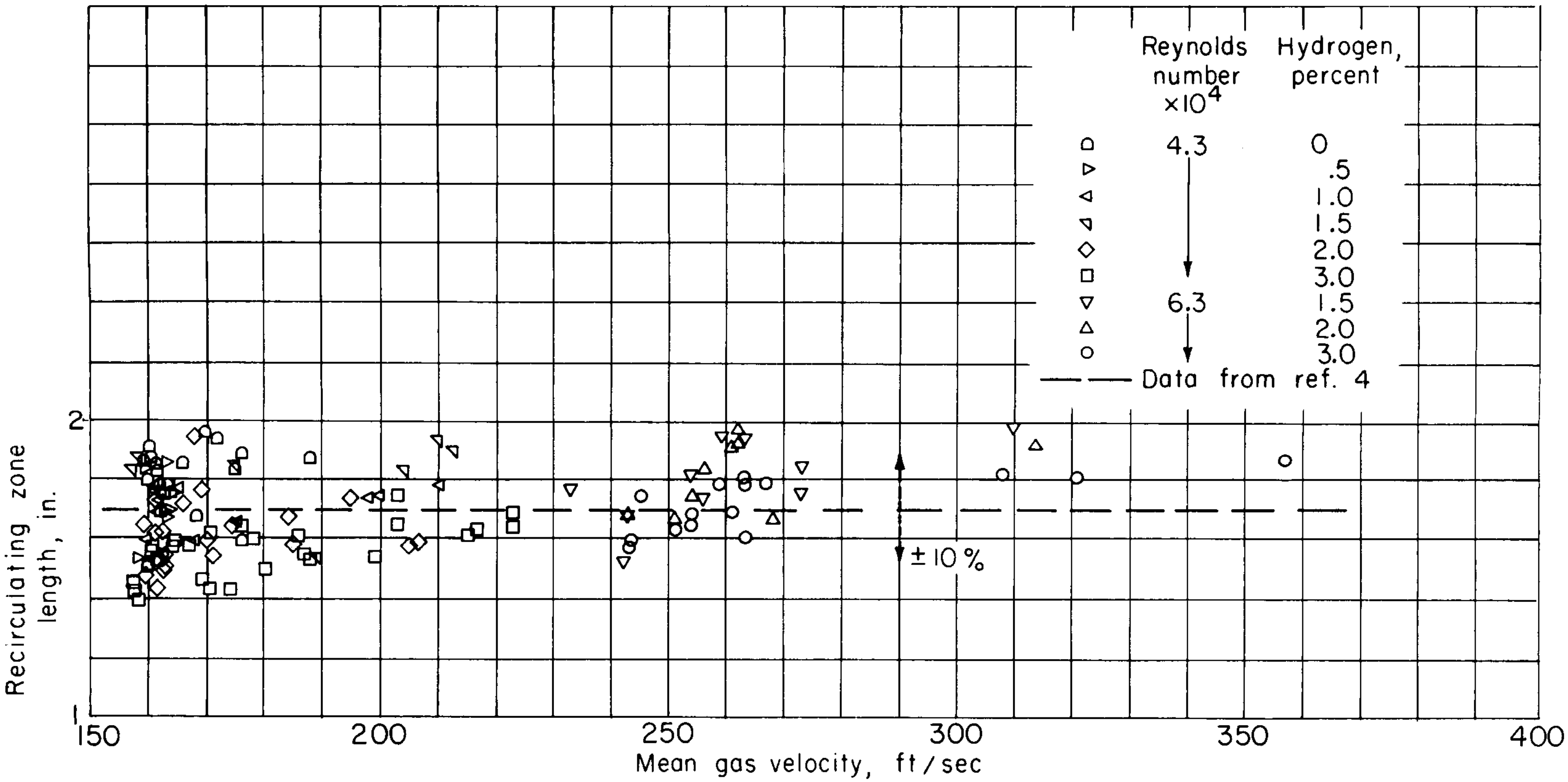

Figure 9. - Recirculation zone lengths for various concentrations of hydrogen additive as a function of main gas velocity.

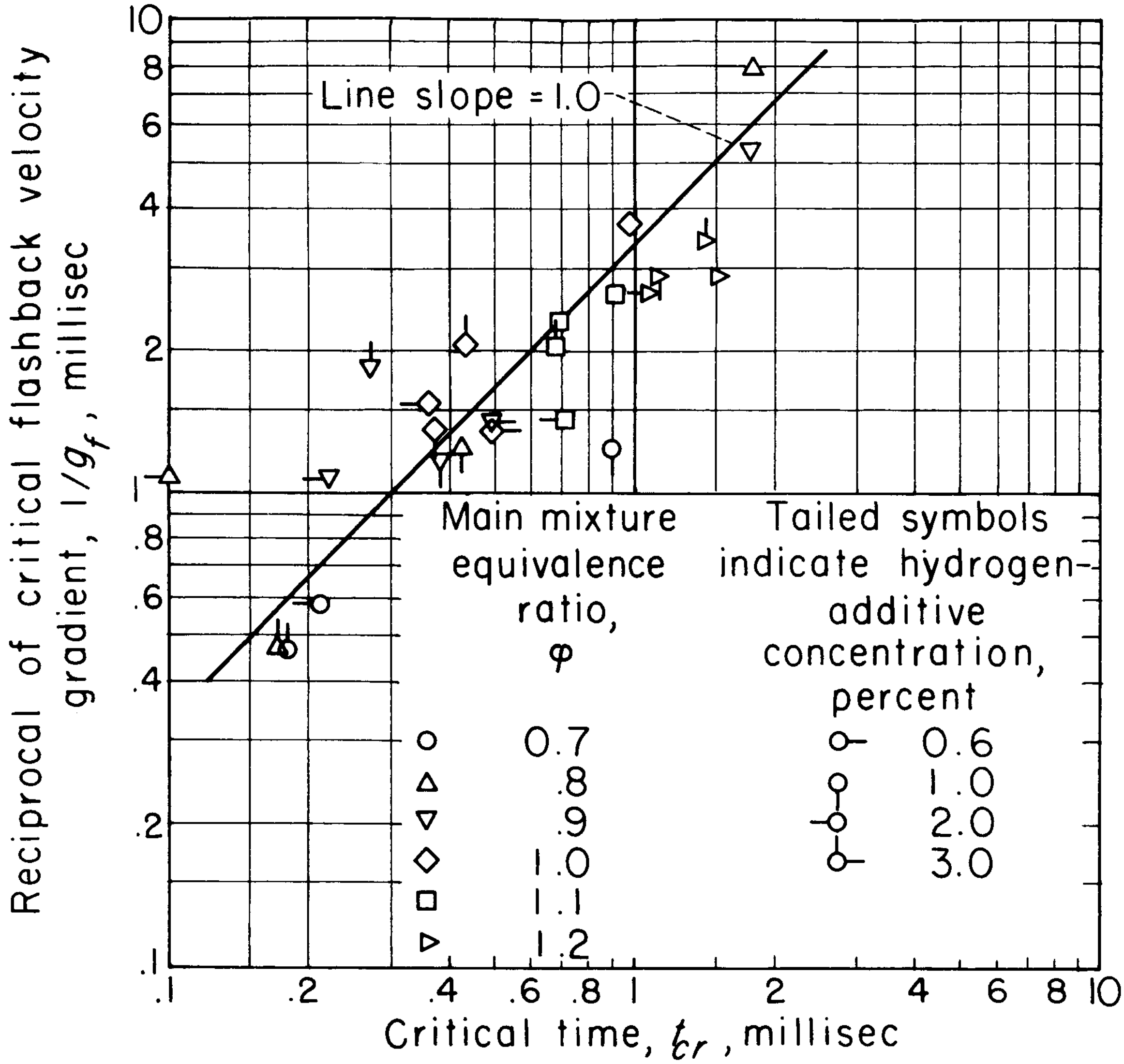

Figure 10. - Comparison of critical time t_{cr} and reciprocal of critical flashback velocity gradient $1/gf$ values for various propane-air mixtures with various amounts of hydrogen additive.

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